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Proof-of-Concept of a Revolutionary Cooling Shirt with a Thermal Manikin

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14. ABSTRACT
Heat-related illness is a critical factor for personnel operating in high heat environments. Traditional cooling technologies are limited by the need for a power supply, the added weight of the product, and the cooling duration. This research investigates a lightweight (47-g), passive cooling textile material provided by Arctic Ease® (Phoenixville, PA) and designed by the United States Air Force School of Aerospace Medicine (USAFSAM/FHC) that offers multiple hours of sustained cooling. The ability to deliver cooling was evaluated using a thermal manikin. Initial research was conducted under dry heat conditions at 35°C/50% relative humidity as the first step to evaluate the technology. Effective cooling rate was determined to be 30 W for the system. Calculations were based on the manikin zones covered by the shirt. Preliminary dry tests indicated a cooling duration longer than 2 hours.

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Heat-related illness, cooling shirt, thermal manikin, military

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1.0 SUMMARY

Battlefield Airmen exposed to heat may experience reductions in physical performance that decrease their work capacity. Reductions in work capacity could severely limit the ability of Airmen to adequately sustain and satisfactorily complete specified duties required during intense ground operations. Physiological stressors caused by heat stress are expressed in individuals as reductions in cardiac output and reduced blood flow to the brain, skeletal muscle, kidneys, and skin tissues. Prolonged work (e.g., 8 hours) in hot, humid environments may also cause dehydration resulting from excessive sweat and associated sodium chloride losses in skeletal muscle, which collectively result in physical and mental exhaustion.

Cooling garment evaluations can be a challenge due to variations among influencing factors. Environmental factors including temperature, humidity, and wind speed need to be controlled to accurately compare the effectiveness of the device. Physiological factors can be influenced by the time of day of the test and the subject's diet, thus affecting the physical or cognitive performance of the research participant. Therefore, environmental chambers and human thermal surrogates are useful tools to gain knowledge on the performance of cooling garments in a controlled environment.

In this study, an epoxy thermal manikin from Measurement Technology Northwest was used to quantify the cooling effect of a gel-based, passive cooling technology inserted into a specially designed T-shirt. Sustained cooling rates of 20 W and 30 W were obtained at 50% and 25% relative humidity during dry tests. With the limited data presented in this paper, it was shown that a change in relative humidity increases measured cooling rate of the product but decreases cooling life. Further testing must be conducted to fully evaluate the garment's limitations and capabilities.

2.0 INTRODUCTION/BACKGROUND

Heat exhaustion is a leading cause of injury in many occupations involving high levels of physical activity or exposure to high temperature environments including military, fire protection, and sports. Battlefield Airmen exposed to heat may experience reductions in physical performance that decrease their work capacity. Reductions in work capacity could severely limit the ability of Airmen to adequately sustain and satisfactorily complete specified duties required during intense ground operations. Physiological stressors caused by heat stress are expressed in individuals as reductions in cardiac output and reduced blood flow to the brain, skeletal muscle, kidneys, and skin tissues. Prolonged work (e.g., 8 hours) in hot, humid environments may also cause dehydration resulting from excessive sweat and associated sodium chloride losses in skeletal muscle, which collectively result in physical and mental exhaustion [1-3].

Personal cooling systems employ active and passive means of cooling the human subject to remove or reduce the effects of overheating. Active systems often use a liquid-based cooling system that circulates a chilled heat transfer medium throughout fluid lines built into the garment construction. Because of the necessity for watertight liquid lines and a pump and/or power source, these systems are often heavy and restrict or inhibit movement. Passive systems are designed to work without the need for a pump or power source and often employ the use of phase change materials (ice, salt, gel) to provide a cooling effect.

Cooling garment evaluations can be a challenge due to variations among influencing factors. Environmental factors including temperature, humidity, and wind speed need to be

controlled to accurately compare the effectiveness of the device. Physiological factors can be influenced by the time of day of the test and the subject's diet, thus affecting the physical or cognitive performance of the research participant. Therefore, environmental chambers and human thermal surrogates are useful tools to gain knowledge on the performance of cooling garments in a controlled environment.

One such option for research of this kind is an epoxy thermal manikin from Measurement Technology Northwest (Seattle, WA). This technological system includes a thermally conductive, aluminum-filled, carbon-epoxy shell manikin representative of a 50th percentile Western male and ThermDAC control software. The thermal manikin includes 34 independent thermal zones, an optional sweating skin that allows for computerized fluid flow, two ambient temperature sensors, one relative humidity sensor, and one wind speed sensor. ThermDAC software both controls the thermal properties of the manikin and allows for real-time data display and logging capabilities. Temperature and relative humidity can be controlled in the environmental chamber. Temperature options range from -20°C to 50°C, and relative humidity ranges from 0 to 100% including condensation [4].

The cooling effects of passive and active cooling vests have been measured using thermal manikins in various studies. The objective of this study was to quantify the cooling effect of a gel-based, passive cooling technology inserted into a specially designed T-shirt using a thermal manikin.

3.0 METHODS

A 34-zone thermal manikin in the form of a 50th percentile human was used to capture the data for this study. The manikin accurately simulates metabolic heat output of the human body using a computer-controlled system of heating elements and sensors. The system also has the ability to sweat via micro-pump-controlled pores; however, this study focused solely on dry testing. Established thermal manikin testing procedures [5,6] were used as a guideline to design this experiment.

The cooling garment textile material was supplied by Arctic Ease® (Phoenixville, PA) and contained 44% pima cotton, 44% MicroModal®, 8% polyester, and 4% spandex. Pockets of the same material were created to fully encapsulate the lightweight cryotherapy pad. The cooling medium is flame resistant to 815°C, adding to the garment's capabilities of meeting Air Force requirements for flame resistance. The shirt weight is 203 grams for a total of 471 grams with the cooling insert.

Before testing, clothing samples were allowed to rest in the controlled environment for a minimum of 12 hours. Initial product concepts involve rechargeable inserts that are added to special garments to obtain the cooling effect. The thermal manikin with cooling garment is pictured in Figure 1.

Chamber conditions were set at 35°C and 50% relative humidity (RH) for the first three sets of three tests and then 35°C and 25% for the next three. Three samples of baseline data were recorded and averaged to confirm that the garment itself was not producing an effect on the manikin. Per manufacturer recommendation, the cryotherapy pads were stored in a refrigerator at 10°C to obtain a maximum effect. New pads were used for each test. Data recording began as soon as product was applied to the manikin and recorded for 2 hours. Heat input to the zones of the manikin was then analyzed and compared to baseline heat input requirements without cooling pads to obtain the maximum cooling effect.

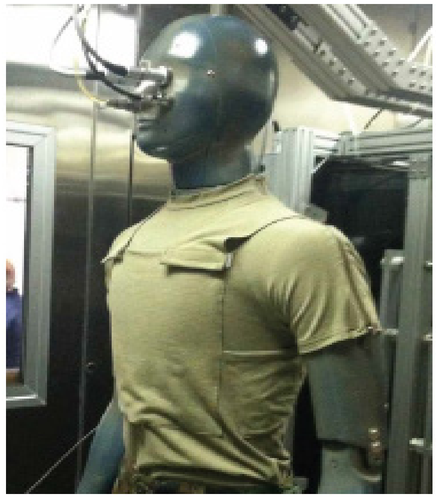

Figure 1. Thermal Manikin with Cooling Garment

4.0 RESULTS

Figures 2 and 3 show the individual zone heat flux results of the two test conditions for the chest, shoulders, stomach, and mid back. The application of the cooling material is limited to the pockets in the garment covering these sections of the body. As a result, the thermal response of the other body sections is negligible. From these two graphs, two clear modes of operation can be determined. Since the product is applied to the manikin at 10°C, the heating elements require an initial spike of energy. Once the cooling medium has reached temperature equilibrium, it is then producing passive cooling through evaporation of the trapped water. Because the chest has the highest surface area of these zones, it also exhibits the largest amount of cooling. In the 25% RH environment, however, the material reaches a point where it dries out and diminishes in cooling capacity. In the 50% RH environment, this drop in cooling capacity does not begin to occur until the very end of the 2-hour period.

Figure 4 compares the total combined wattage of the four zones at both environmental conditions. At the lower RH of 25%, the cooling effect is higher than that of the higher RH environment because of the large gradient in moisture available in the cooling medium compared with surrounding air. This effect begins to drop off somewhere around 1 hour as the moisture content of the cooling medium is reduced.

5.0 CONCLUSIONS

Sustained cooling rates of 20 W and 30 W were obtained at 50% and 25% relative humidity during dry tests using a thermal manikin. The cooling power per weight of the system tested was 64 W/kg. Compared to the 42 W/kg found with the ice vest tested by Smolander et al. [7], this is a 50% improvement. However, effectiveness of low level cooling on the human body must be taken into consideration. As discussed in Dionne et al. [8], measured cooling rates of a given system will be affected by skin moisture. As the system studied in this paper relies on evaporative cooling to produce an effect, availability of airflow must also be taken into account.

With the limited data presented in this paper, it was shown that a change in relative humidity increases measured cooling rate of the product but decreases cooling life. Further testing must be conducted to fully evaluate the garment's capabilities.

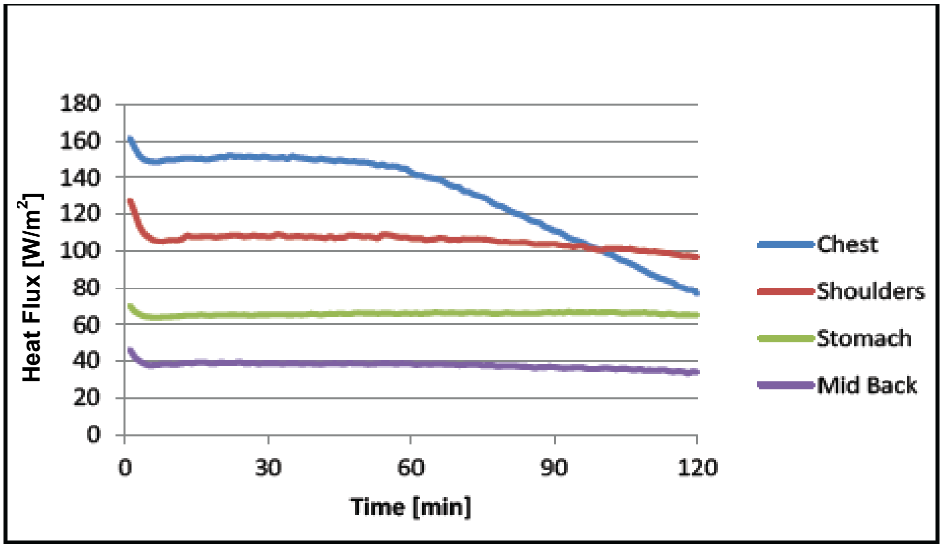

Figure 2. Measured Heat Flux, 35°C, 25% RH

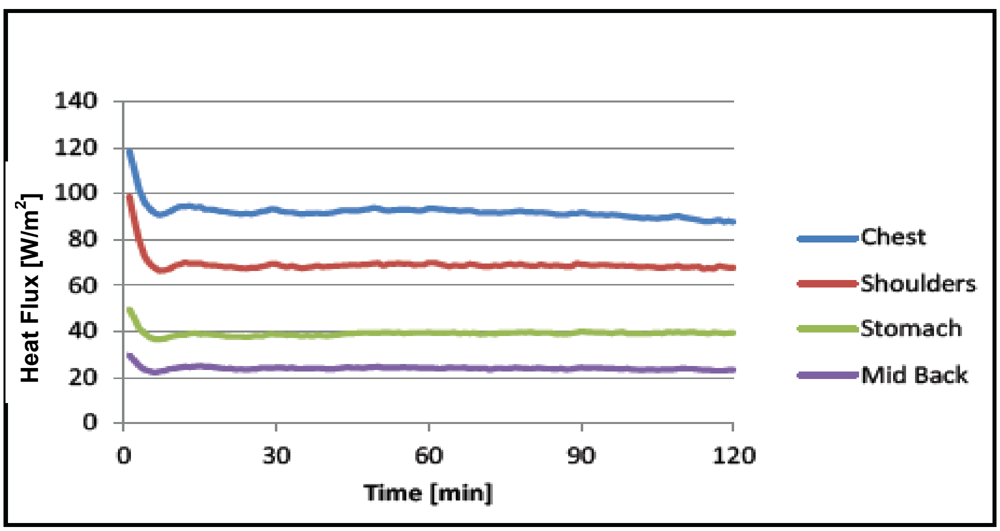

Figure 3. Measured Heat Flux, 35°C, 50% RH

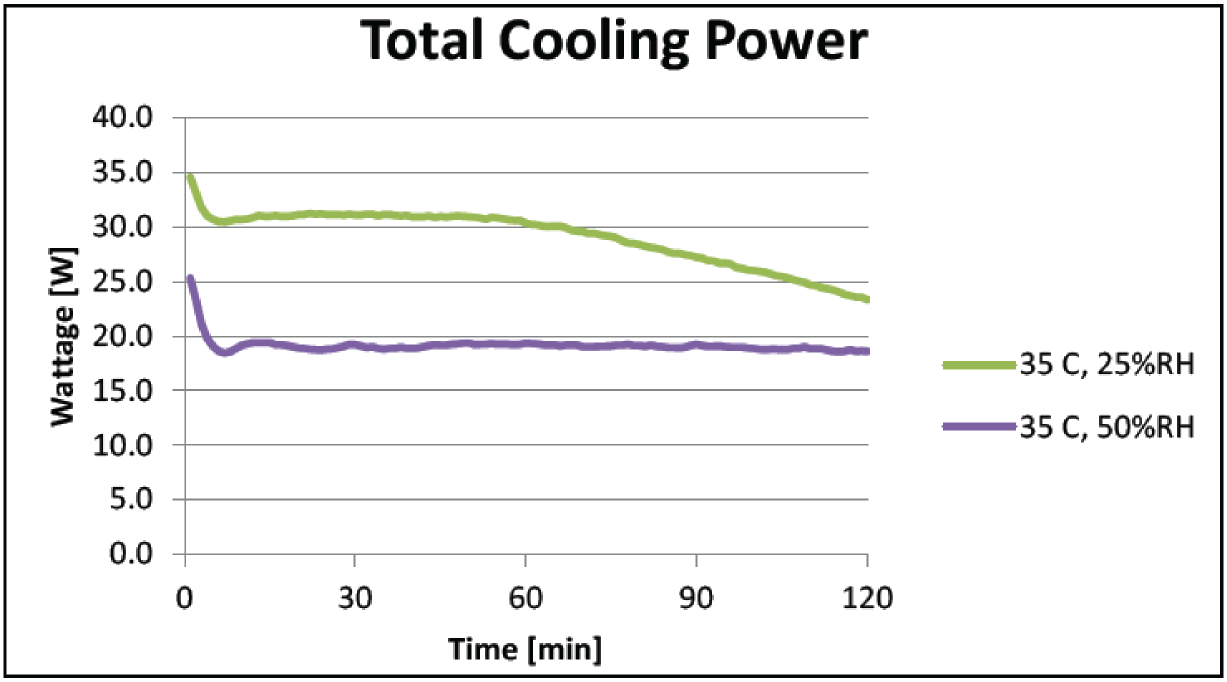

Figure 4. Total Cooling Power

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